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Two component model with collective flow for hadroproduction in heavy-ion collisions.

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Abstract

The spectra shape of produced charged hadrons on the size of a colliding system is discussed using a two component model. The hierarchy by the system-size in the spectra shape is observed. Next, the hydrodynamic extension of the model is suggested to describe the spectra of charged particles produced in heavy-ion collisions in the full range of transverse momenta, p_T. Data from heavy-ion collisions measured at RHIC and LHC are analyzed and combined in terms of energy density.The observed regularities might be explained by the formation of QGP during the collision.

Keywords: particle production, heavy ions, phenomenology, two component model, hydrodynamic

1. Introduction

In high-energy collisions hadroproduction can be described by two distinct mechanisms [1, 2]. The charged particle spectra are aproximated as a function of the particles' transverse momentum p_T by a sum of an exponential (Boltzmann-like) and a power-law distributions:

$$\frac{d\sigma}{p_T dp_T} = A_e \exp\left(-E_{Tkin}/T_e\right) + \frac{A}{(1+\frac{p_T^2}{T^2 \cdot N})^N}, \qquad (1)$$

where $E_{Tkin} = \sqrt{p_T^2 + M^2} - M$ with M equal to the produced hadron mass. A_e, A, T_e, T, N are the free parameters obtained from the fit to the experimental data. The exponential term stands for the release of 'thermalized' particles by the preexisting valence quarks and a quark-gluon cloud coupled to them inside the colliding baryon. The power-law term accounts for the fragmentation of mini-jets formed by the secondary partons produced at the first stage of the collision.

In this work is to compare the shapes of charged hadron spectra produced in $\gamma\gamma$ and pp interactions [2, 3] with a more complex case of heavy-ion collisions.

2. Hierarchy in hadroproduction dynamics

ALICE Collaboration [4] provides data on lead-lead collisions in the range of transverse momentum p_T up to 50 GeV. Figure 1 shows experimental data on $\gamma\gamma$ [5], pp [6] and PbPb [4] collisions fitted with the parameterization introduced (1). From the shape of the PbPb collision's spectrum one can notice that an additional power-law term is needed to describe the data in terms of the introduced approach :

$$\frac{d\sigma}{p_T dp_T} = A_e \exp\left(-E_{Tkin}/T_e\right) + \frac{A}{(1+\frac{p_T^2}{T^2 \cdot N})^N} + \frac{A_1}{(1+\frac{p_T^2}{T_1^2 \cdot N_1})^{N_1}} \qquad (2)$$

Figure 2(a) shows an important variable R_{AA} for PbPb collisions measured at ALICE [4] together with contributions from the three terms of eq. (2) independently, each of them divided over the spectrum in pp-collisions measured at the same c.m.s. energy [6]. Studying of the R_{AA} for lead-lead collisions at ALICE [4] can help

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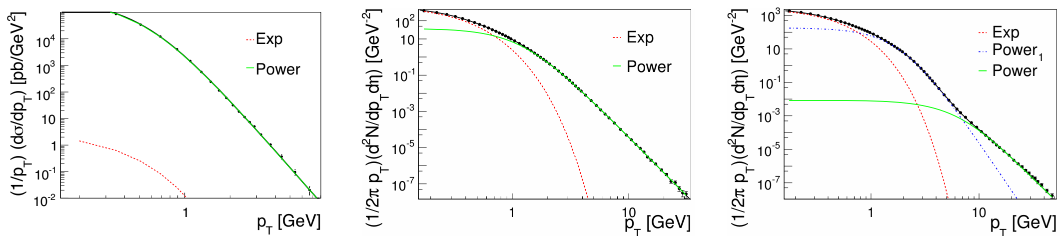


(a) (b) (c)

Figure 1: Charged particle spectra in $\gamma\gamma$ [5] a), pp [6] b) and in central PbPb collisions [4] c) fitted to the function (2): the red (dashed) line shows the exponential term and the green (solid) and blue (dash-dot) lines - two power-law terms.

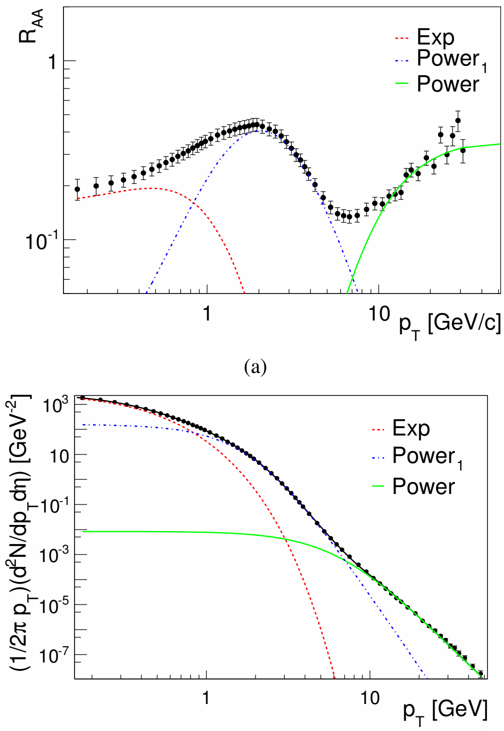
us to understand the following picture of hadroproduction [7]:

1. The bulk of low-p_T particles originates from the 'quark-gluon soup' formed in the heavy-ion collision and has an exponential p_T distribution, as shown by the red dashed line in Figs. 1 and 2.
2. The high-p_T tail (green solid line in Figs. 1 and 2) accounts for the mini-jets that pass through the nuclei. When these jets hadronize into final state particles *outside* the nuclei, we get the same power-law term parameter N as in pp-collisions (Figs. 1 b) and c)), resulting in a constant suppression (R_{AA}) of high-p_T (> 20 GeV) particles (Fig. 2). Passing through the nucle, the jets should lose about $\frac{dE}{dz} \cdot R_A \sim 7$ GeV [8], R_A is the radius of the nuclei and hadrons with $p_T < 7$ GeV will be suppressed.
3. However, if the mini-jet fragmentation occurs before the produced particles leave the nuclei volume, they are affected by multiple rescatterings from the media, lose energy and their distribution (blue dash-dot line in Fig. 1 and 2) becomes closer to the exponent.

One can see, hadroproduction dynamics can be characterized by complexity of the colliding system: $\gamma\gamma$ collisions, pp-collisions, heavy-ion collisions.

3. Hydrodynamic extension of the model

In heavy-ion collisions, when a large colliding system is formed, one should also take effects of the 'collective motion' into account [9] and the particle production is usually considered in terms of relativistic hydrodynamics. Therefore, we modify the introduced approach (1) using recent theoretical calculations [9]. The idea of hydrodynamic approach is that the thermalized system expands collectively in longitudinal direction generating the transverse flow by high pressure in the colliding system. The distidution is still Boltzmann, but it



(b)

Figure 2: (a): R_{AA} measured for central Pb-Pb collisions [4] shown with the terms of (2) independently divided over the fit (1) of the pp-data at the same c.m.s energy: the red (dashed) line shows the exponential term and the green (solid) and blue (dash-dot) lines - two power-law terms. (b): Central lead-lead collisions [4] fitted with (4): the red (dashed) line shows the hydrodynamic term and the green (solid) and blue (dash-dot) lines - two power-law terms.

is boosted to the expanding system. According to this approach, the radiation of thermalized particles can be parameterized by the following formula:

$$\frac{\mathrm{dn}}{p_T \mathrm{d}p_T} \propto \int_0^R r\,\mathrm{d}r\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_e}\right) K_1\left(\frac{m_T \cosh\rho}{T_e}\right), \tag{3}$$

where $\rho = tanh^{-1}\beta_r$ and $\beta_r(r) = \beta_s(\frac{r}{R})$, with β_s standing for the surface velocity. We take $\beta_s = 0.5c$ which is consistent with previous observations [9]. We substitute the exponential term in (1) by (3) and use this hydrodynamic approach to fit the recent experimental data on PbPb collisions measured by the ALICE [4] at $\sqrt{s} = 2.76$ TeV, shown in Fig. 2(b) together with the fit:

$$\frac{\mathrm{d}n}{p_T \mathrm{d}p_T} = A_e \cdot \int_0^R r\,\mathrm{d}r\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_e}\right) K_1\left(\frac{m_T \cosh\rho}{T_e}\right) + \frac{A}{(1 + \frac{p_T^2}{T^2 \cdot N})^N} + \frac{A_1}{(1 + \frac{p_T^2}{T_1^2 \cdot N_1})^{N_1}} \tag{4}$$

Hydrodynamic extension slightly modifies the description of data and an additional power-law term is still needed. But the temperatures T_e obtained from the fits with and without transverse flow taken into account differ significantly [12] (Fig. 3)

4. Freeze-out temperature

The thermalized production of charged hadrons (described by function (3)) can be extracted from the whole statistical ensemble and in this paper it is proposed to study the variations of the temperature-like parameter T_e in (3) with the centrality and the c.m.s. energy in heavy-ion collisions. It is interesting to consider the experimental data measured at RHIC and LHC together and combine it in terms of energy density. In this paper we consider the experimental data measured in AuAu collisions at $\sqrt{s} = 200$ GeV/N and $\sqrt{s} = 130$ GeV/N by PHENIX [13, 14] and PbPb collisions at $\sqrt{s} = 2.76$ TeV/N by ALICE [4].

Having calculated the energy density ε based on theoretical caculations [15], one can plot the temperature T_e extracted from (4) as a function of it, as shown in Fig. 3. A smooth transition in the T_e values between ALICE and RHIC measurements is observed.

One can notice interesting behavior of the temperature T_e as a function of energy density ($\varepsilon \propto T_e^4 + B$), which is in a good agreement with the Bag model [16], Fig. 3. The temperature T_e of the final state particles reaches a certain limit for high energy densities. This might be explained from QGP theory that considers the phase transition temperature T_c from QGP to final state hadrons. For high values of ε one can notice, that the observed freeze-out temperature is $T_{fo} \approx 145$ MeV, and is slightly below the critical temperature $T_c \sim 155 - 160$ MeV for QGP obtained in different calculations [17, 18]. That gives us another confirmation of applicability of such an approach (4) to decribe hadroproduction in heavy-ion collisions.

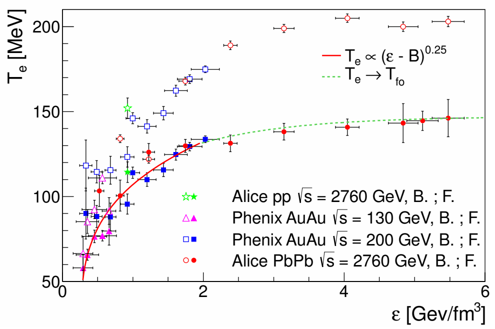


Figure 3: Temperature of the final state hadrons coming from the 'thermalized' part of the spectra in heavy-ion collisions as a function of energy density. Full points show the results extracted from the fit by taking into account the collective flow 4 (F. in the legend); open points show the results when using a fit with the Boltzmann exponent (2) (B. in the legend). Solid line stands for the $T_e \propto (\varepsilon - B)^{0.25}$ fit and dashed line shows $T_e \to const$ behavior.

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